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Stability Study of Low-Inertia Hybrid Power Systems

Anand Prakasha
M.Sc.
Electrical Engineering Faculty (EEMCS)
Technical University of Delft (TU Delft)
Delft, The Netherlands

Dr. J. L. Rueda Torres,
Associate Professor
Electrical Engineering Faculty (EEMCS)
Technical University of Delft (TU Delft)
Delft, The Netherlands

Dr. V. Chayapathi,
Associate Professor
Department of Electrical Engineering
R. V. College of Engineering (RVCE)
Bengaluru, India

Abstract— **In the modern world, the electrical load demands are increasing at an exponential rate. The increasing power demands has led to formulation of several policies for the deregulation of the electricity. To supply the increasing load demand, renewable sources are integrated to the conventional grids. The HVDC technology has proved to be a reliable way to integrate the renewable sources successfully to partially supply the power demand. The integration involves many challenges like incorporating different sources with various sophisticated mechanisms and technologies. Among them, one of the challenge is the system stability when the low inertia machines are a predominant source in a weakly meshed grid. In this paper, the system stability of the system is addressed. Two generic case studies are examined to study the effect of machine inertia on the Small-Signal Stability (SSS). The results from the linearized models are compared with the results obtained from the transient time domain signals.**

Keywords— Eigenvalues; HVDC convertors; Prony analysis; Hybrid power systems

I. INTRODUCTION

The demand for electricity has grown exponentially in the recent past. To meet the increasing demand, the power grids have grown into highly complex non-linear systems for the transmission of electrical power. The traditional Thermal and Gas power plants have negative effects on the environment causing air pollution, water pollution and greenhouse effect. To mitigate the negative effects on the environment and cope with the increasing load demand, they are integrated with renewable sources of generation like Wind, Hydro, and Solar etc. To achieve bulk power transmission over long distances and successful integration of renewable sources, the High Voltage Direct Current (HVDC) transmission technologies are introduced to the transmission system. This system has lower transmission losses compared to the HVAC transmission system of the same capacity and has a lower investment cost for long distance transmission. Due to the limitations of Line Commutated Convertors (LCCs), the Voltage Source Converters (VSCs) are incorporated for modern transmission network applications [1]. The VSCs incorporate modern electronic switches like IGBTs and GTOs that are self-commutating and change the polarity of power flow by changing the direction of the current flow. As a consequence, the renewable sources of energy like wind farms, tidal power and hydro generators are incorporated into the electrical generation sector [2].

A high degree of safety and permissible operating conditions of the power systems, is achieved by an in-depth analysis of its operation, planning and dynamic studies. This is achieved by developing detailed models of the power networks and study their behavior against events like short-circuits, line outages, load changes etc. Very accurate models are developed to carry out in-depth studies in advanced softwares, such as RTDS [3], PSCAD, EMTP, PSSE and DIgSILENT Powerfactory. Among these, DIgSILENT Powerfactory is the most advanced software for transient and stability studies.

II. LITERATURE

A power system has to withstand disturbances of various magnitudes to supply an uninterrupted power to all the utilities. Further, the system should be designed and operated such that the all the probable contingencies are sustained without losing the loads and the most adverse possible contingencies do not result in widespread interruptions. The authors. M. Klein et.al in [4] studied the different electromechanical modes that exist in a weakly interconnected power system in 1920s. The weakly meshed system described in [5] is used extensively to study the SSS of the power systems. SSS is an important factor in meshed power systems consequence of which more research has gone into this area of power system studies. In the modern times, due to the introduction of renewables like wind, hydro and solar, stability is one of the most critical and challenging issues that needs to be addressed when the penetration of renewables is increasing day to day. P. Bresesti et.al in [6] studied the different topologies of wind farms and their interconnection with HVDC links. This gives an insight to different way to connect wind farms to mitigate the transmission losses and optimal voltage levels to transmit the generated power.

The introduction of HVDC technology has led to different challenges including modelling Voltage Source Converters (VSC) and different control strategies to control the power transmission as discussed in [7]. The space vector theory gives a more general approach to power systems which is discussed by the authors in [8]. When the system is stressed (operating at peak load), there are inherent electromechanical oscillations between generators within an area or between areas. In the publications [9] and [10] the dominant modes of oscillations are identified in an integrated Multi-Terminal Direct Current (MTDC) power system which is designed to resemble the future HVDC (MTDC) networks. These inherent power system oscillations can arise due to disturbances in the power system operating condition or when the steady state boundaries of the various components in the system are crossed. These oscillations can be troublesome to the power system if they are not damped within a certain time. The authors in [11] discuss about tuning the controllers to damp the oscillations in an MTDC network using Evolutionary Particle Swarm Optimization (EPSO) approach.

The modern hybrid (HVAC-HVDC) grids incorporate VSC converter terminals as the dynamic devices whose interaction with AC system, their modelling and control strategies has generated a lot of interest in recent years [12]. The studies on system planning and integration of different renewable sources focuses on specific fulfilment of technical requirements determined explicitly. These requirements include both static and dynamic constraints. But in the modern times, due to increasing environmental concerns, there is an increasing demand towards incorporating low inertia machines (like wind turbines, small hydro turbines). The inertia constant being an inherent property of synchronous machines, the grid frequency and the dynamics following the small disturbances is governed by the mass properties of the machines. This is a critical issue to be addressed in weakly meshed grids, where low inertia machines are the predominant sources. In the foreseeable future, there shall be more incorporation of HVDC links into the existing grids. So there is an increasing demand to address the SSS issues in low-inertial power systems from the system integration point of view by examining the effect of incorporating low inertia machines into the existing system.

This paper mainly focuses on the small-signal stability analysis of power systems with an integrated HVDC link. In this work, the SSS of the power system when low inertia machines are introduced into an existing grid is addressed. Two generic case studies are defined in order to evaluate the effect of machine inertia on the SSS in a large power system.

III. CASE STUDIES

To examine the effect of incorporating low inertia machines on the stability of the system in HVAC conditions and hybrid conditions, two test cases are developed from the classical two-area system described in [5]. The Fig.-1 shows the classical two-area system. All the sources in the system are modelled as 6th order synchronous machines with different inertia constants H. The values of H are tabulated in Table-I. In this study, area-1 and area-2 are considered as thermal power plants and the third area is considered to be a hydropower plant. The developed power system for case study-1 is shown in the Fig.-2. In this system, the third area is interconnected to the two-area system by an HVAC transmission line. In case study-2, the HVAC tie line is replaced by a point-to-point HVDC link.

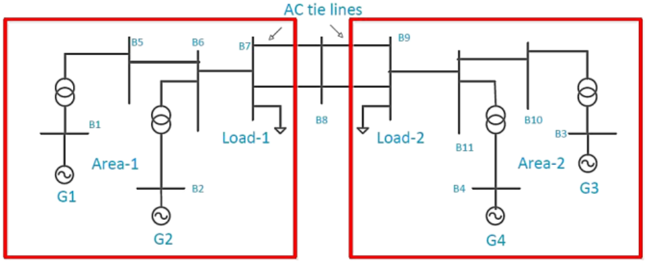

Fig. 1 Classical Two area system

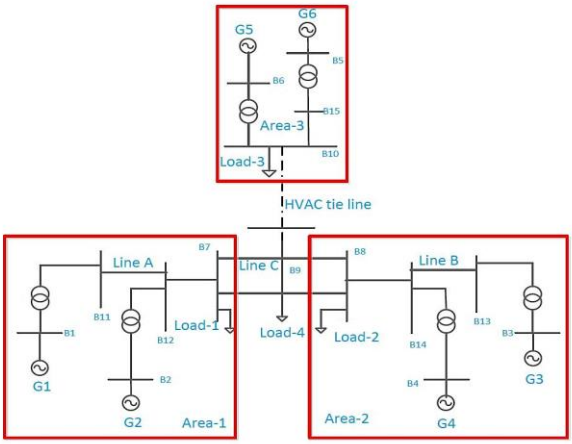

Fig. 2 Developed Three-area HVAC system

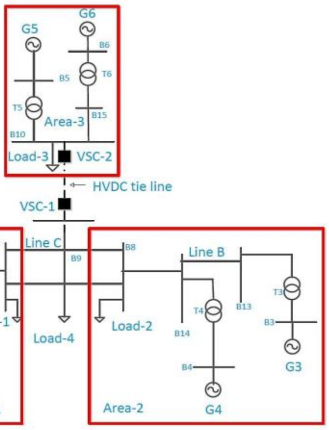

Fig. 3 Developed Three-area HVAC-DC Hybrid system

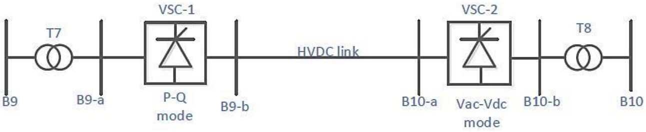

Fig. 4 Implemented Point-to-Point HVDC link

The Fig.-3 depicts the developed power system for case study-2. The implemented point-to-point HVDC link is shown in the Fig.-4. The VSC-1 is set to P-control mode to control the active power on the DC line and the VSC-2 is set to V_{ac}-V_{dc} control mode to control the AC and the DC bus voltage respectively. The inner control loops have unity gains for both the VSC’s. The P control loop has a gain of 2000 for proportional gain and 5000 as the integral gain. For the VSC-2 the proportional gain is set to 1500 and the integral gain is set to 5000 respectively.

TABLE I. GENERATORS AND INERTIA CONSTANTS

Generators	G1	G2	G3	G4	G5	G6
Initial Inertia (H)	6	4	10	7	4	3

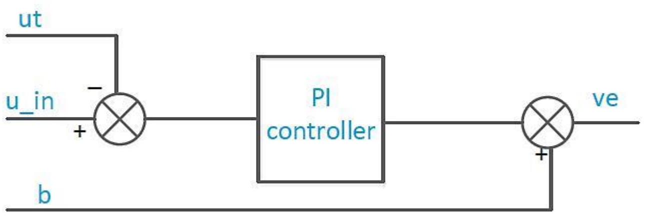

Fig. 5 Implemented Automatic Voltage Regulator (AVR) system

The implemented automatic voltage controller (AVR) is shown in the Fig.-5. The AVR is implemented as a simple PI controller which takes in the error (E_{error}) between the stead state voltage 'uin' and the terminal voltage 'ut' to control the field voltage 've' of the synchronous machine. The auxiliary signal 'b' is taken to force the state variable to be zero in the initial conditions. The PI controller is defined by (Ke+Kie/s) for AVR. The state equation of the AVR is given by the equation-1

$$s=(E_{error}*K_{ie})/(ve-(E_{error}*K_{e})-b) \quad (1)$$

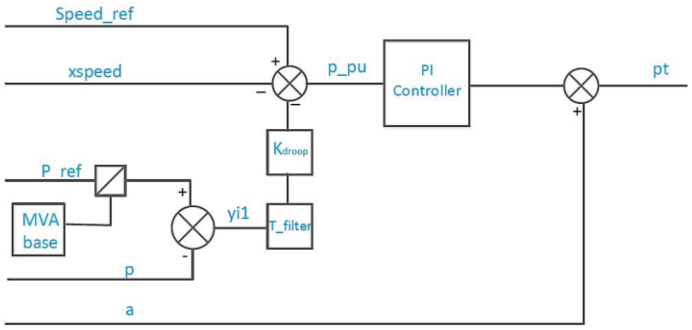

Fig. 6 Implemented Turbine Speed Governor (GOV) system

The implemented speed governor (GOV) has two loops as depicted in Fig.-6, PI controller loop is the primary loop for speed control defined by (K_g+K_{ig}/s), and the loop with active power inputs is the droop control loop. The auxiliary signal 'a' is defined to force the state variable to zero in initial conditions. The state equation for the governor is given by the equation-2.

$$s=(p_{pu}*K_{ig})/(pt-a-(p_{pu}*K_g)) \quad (2)$$

IV. IMPLEMENTED METHODOLOGY

In this study, small signal stability analysis by Eigenvalue approach and transient stability analysis are used. From Eigenvalue analysis approach, the different electromechanical modes are determined in the case studies. The system Eigenvalues, Eigenvectors and Participation factors are computed for both the case studies for different values of inertia constant H. By the spectral analysis of the transient signals, the modal analysis results are verified for the case studies. The modal analysis study is carried out in DIgSILENT powerfactory simulation environment and the spectral analysis of the transient signals was done by the open source Prony analysis toolbox. The inertia constants of the synchronous machines are varied as given in the table-1. As a result, the Eigenvalues corresponding to the local modes and the inter-area modes of the system are affected significantly. Eigenvalues corresponding to each set of values for H is calculated for comparison. Different scenarios are considered to obtain the transient time-domain signals. These signals are analyzed to extract the modal information.

V. RESULTS

A. Effect of machine inertia on the Eigenvalues

In the classical two-area system, there are two local modes of frequencies 1.522 Hz and 1.122 Hz corresponding to area-1 and area-2 respectively and one inter-area mode between two areas of frequency 0.689 Hz. In the case studies, the systems are tuned to transfer the active power from the third area to the rest of the system. The Eigenvalues are plotted for different inertia constants by linearizing the system. The Eigen values are plotted for different values of inertia and the critical Eigen values corresponding to the local area modes and the low frequency inter-area modes are plotted in the Fig.-7 for case study-1 and in the Fig.-8 for case study-2 respectively.

In the case study-1 with all the areas connected with HVAC tie-lines, it is observed that there are five distinct group of Eigenvalues corresponding to three local area modes and two groups of inter-area modes. One inter-area mode exists between area-1 and area-2 and the other inter-area mode exists between area-1 and area-3. There is no inter-area mode between area-2 and area-3 because, the active power flow between these areas are high due to the load demand. between area-1 and area-2 and the other inter-area mode exists between area-1 and area-3. There is no inter-area mode between area-2 and area-3 because, the active power flow between these areas are high due to the load demand.

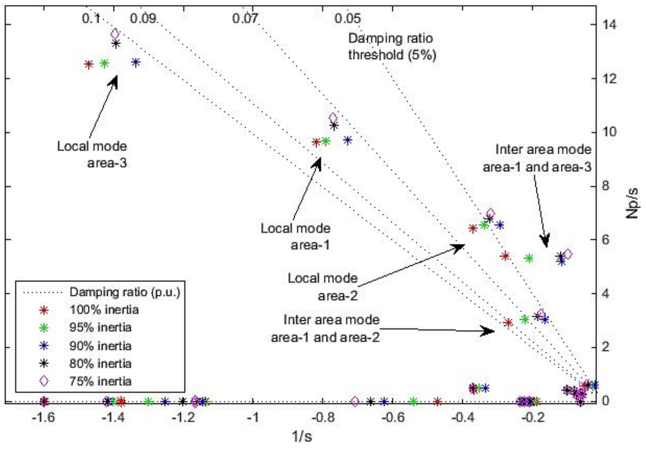

Fig. 7 Eigenvalue plot for study case-1

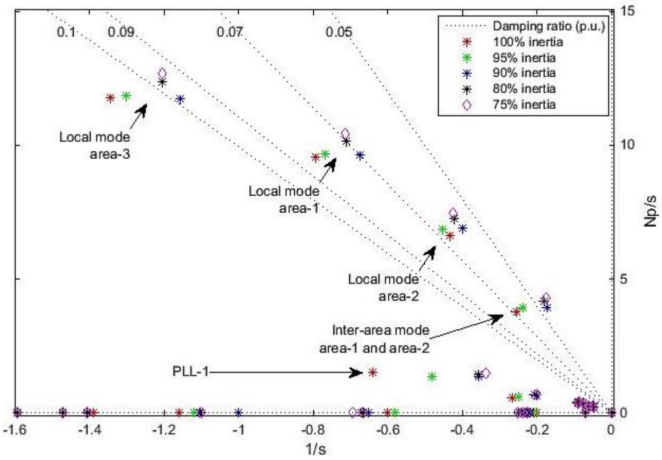

Fig. 8 Eigenvalue plot for study case-2

between area-1 and area-2 and the other inter-area mode exists between area-1 and area-3. There is no inter-area mode between area-2 and area-3 because, the active power flow between these areas are high due to the load demand. Another observation is as the inertia constant of the machines are decreased, the Eigenvalues are moving towards the imaginary axes. This indicates that low inertia machines are more vulnerable to faults in an integrated system. It was observed that the oscillating frequency increases and the damping coefficient decreases with the decrease in the machine inertia. This is because low inertia machines oscillate for a longer time following a disturbance, i.e. they are less stable because of the low stored kinetic energy compared to the high inertia machines. It is also observed that the inter-area modes have a higher frequency between areas with low inertia machines compared to that of high inertia machines. This is again due to the stored kinetic energy in the rotating mass, implicating the higher inertia machines are much more stable compared to the low inertia machines.

In the case study-2 the third area is interconnected by a point-to-point HVDC link as shown in the Fig.-3. The Eigenvalues are plotted for different values of machine inertia constants similar to case study-1. It is observed that there are four distinct groups of Eigenvalues. They belong to the local modes of three areas and inter-area mode between area-1 and area-2. Compared to case study-1 there is only one inter-area mode in case study-2. This is because the second inter-area mode is completely damped out as the third area is interconnected by an HVDC link. In this case, the third area behaves as an independent system.

B. *Comparison between developed case studes*

This study focuses mainly on monitoring the low frequency electromechanical modes in a hybrid power system when a new area is integrated into the existing system. In Table-II, the frequency in Hertz (Hz) (first values) and damping ratios in percentage (second values) of the electromechanical modes is compared with respect to inertias between the two case studies. It is observed that the third area local mode has a higher frequency and damping in case study-1 compared to case study-2. This is because in case study-1, the resulting damping is a cumulative effect of all the six generator controllers whereas in case study-2, the local mode in area-3 is damped by only two generator controllers. The frequency of the inter-area mode in case study-2 is higher compared to that of case study-1due to the higher power transferred by the HVDC link (800 MW) compared to the HVAC link (655 MW).

TABLE II. COMPARISON BETWEEN STUDY CASES

% of H	Case Study-1 Local mode 3	Case study-1 IA A-1 & A-2	Case Study-2 Local mode 3	Case Study-2 IA A-1 & A-2
100 %	1.995, 11.822	0.537, 7.044	1.873, 11.348	0.598, 6.713
95 %	2.016, 11.717	0.545, 6.534	1.889, 10.902	0.624, 6.002
90 %	2.006, 10.692	0.548, 4.505	1.869, 9.805	0.629, 4.349
80 %	2.118, 10.564	4.478, 0.593	1.969, 9.692	0.664, 4.326
75 %	2.172, 10.329	0.593, 4.135	2.017, 9.453	0.682, 4.052

C. *Eigenvalue sensitivity*

The sensitivity of the Eigenvalue to a parameter in the state matrix is given by the participation factor, which is a combination of the right and the left Eigenvectors. In the Fig.-9 and Fig.-10, the participation factor and the right Eigenvector corresponding to local mode of area-1 is presented. From the right Eigenvector compass plot, it is clearly observed that the machines with low inertia have a higher magnitude as a result, the low inertia machine is more sensitive as depicted by the participation bar plot. The Fig.-11 and Fig.-12 depicts the participation factors and the mode shape of the inter-area mode between area-1 and area-2. A similar observation can be made from these plots regarding the sensitivity of the machine inertia for other machines.

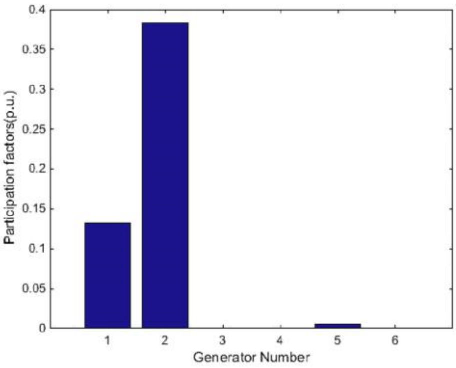

Fig. 9 Participation factors of Local mode area-1

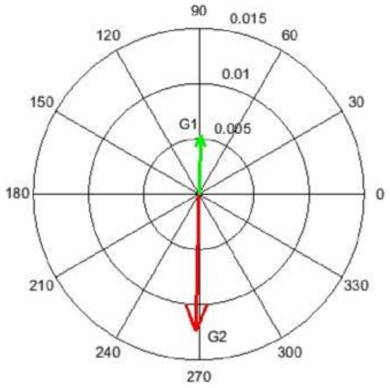

Fig. 10 Right Eigenvectors of Local mode area-1

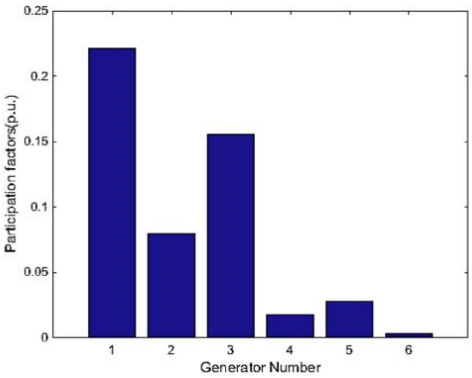

Fig. 11 Participation factors of Inter-area mode area-1 and area-2

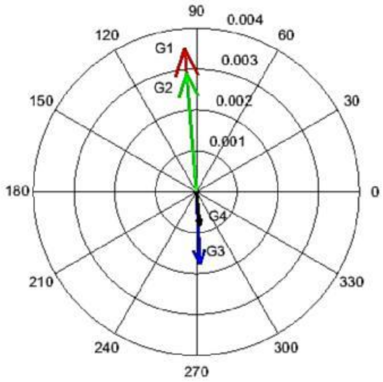

Fig. 12 Right Eigenvectors Inter-area mode area-1 and area-2

D. Time domain analysis

For the time-domain analysis, different scenarios are considered to excite the dominant modes. By Prony analysis toolbox the signals are analyzed to identify the modal frequencies, damping ratios and the amplitudes of oscillations. This method is coupled with Fourier analysis to provide sufficient information regarding the stability for large power systems, where Eigenvalue analysis is not accurate and it is tedious to compute the plant matrix with more than 500 state variables. In this method, a part of the transient signal is analyzed by fitting it over a signal sampled at equal intervals of time. A small window is opened in the single and the spectral analysis is done to obtain the modal information present in the signal. The different scenarios considered in this work is tabulated in the Table-III.

TABLE III. TIME DOMAIN SCENARIOS

Type of Disturbance	Element of the system	Excited mode
Step in generator torques	G1 and G2	Local mode area-1
Short-circuit	Line B	Local mode area-2
Step in generator torques	G6	Local mode area-3
Line outage	Line-C	IA area-1 and area-2

E. Comparison between Frequency domain and Time domain analysis

The complete comparison between linearized modelling in DIgSILENT Powerfactory and the time domain analysis done by Prony analysis toolbox is presented in the Fig.-13. It is observed that the values obtained with the implementation of the controllers do not match completely as compared with that of the case without the generator controllers. This is due to the additional auxiliary loop that is considered for tuning the controllers. The loops do not effectively damp the modes as the controller is partially blocked with the loops.

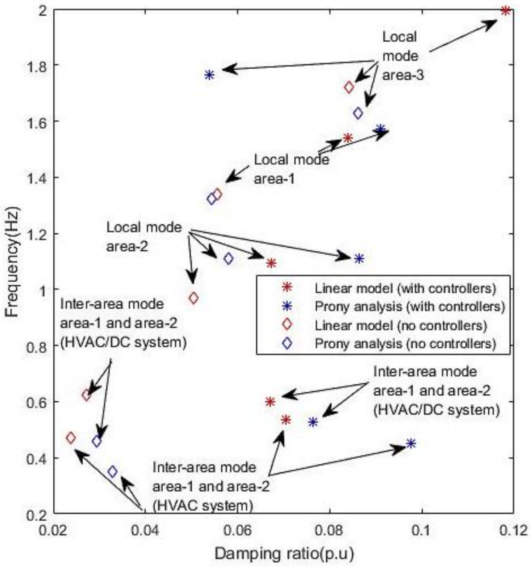

Fig. 13 Comparison between Frequency domain and Time domain analysis

VI. CONCLUSIONS

In this section, the conclusions of this work are presented. In this paper, the effect of low inertia machines on the modal behavior of the system when an HVDC link is incorporated to the existing grid with weak tie lines is investigated. A two-area system is implemented and thereafter, two study cases are developed. In the first case the third area is interconnected with an HVAC tie line and the second case the HVAC tie-line is replaced with a point-to-point HVDC link. The modelling involved the implementation of VSC-HVDC point-to-point link. Synchronous machines with different inertias at peak loaded conditions are considered to examine the sensitivity of the Eigenvalues towards machine inertias. The Eigenvalue sensitivity towards the inertias of the machines was analyzed for both the test cases. The results obtained by linearizing the system was found to be closely matched with the results obtained from the transient time-domain simulation results. The following conclusions are derived from this work:

- The damping of the modes depends on the dynamic elements of the system like the speed governors and exciters. The frequencies of the modes depend on the topology of the network, operating conditions and loading conditions.
- Three local modes are present in both the study cases belonging to three areas respectively. The low inertia machines are more sensitive; hence they swing with a greater amplitudes compared to the high inertia machines. The local modes are independent of the type of tie-line used.
- The inter-area modes are damped out when a HVDC link is incorporated into the existing HVAC system. However, the inter-area mode between areas interconnected with HVAC lines continue to persist (between area-1 and area-2).
- The power flow between area-2 and area-3 was observed to be higher compared to the power flow between area-1

and area-3 and it was observed that the generators with higher inertia settle to a steady state quickly compared to their counterpart as a result, the inter- area mode between area-2 and area-3 does not exist in the case studies considered.

- The Prony window was chosen manually. The mismatch in the curve fitting and manually determining the widow timings is one of the reasons for not obtaining the exact values of frequencies and damping ratios compared to the linearized approach.
- The effect on the damping with and without the generator controllers has significant differences, this is because of the auxiliary loops used in the control system. The signals ’a’ and ’b’ is used in tuning the controllers by decoupling the PI controller from the output signals, but they do not damp the modes effectively.

It is concluded that both the methods can be used for analysis of power systems. By Prony’s approach, there may be many modes excited due to the disturbance in the system, as a result, it is tedious to verify the given mode is an electromechanical mode or not. Linearization can be applied to small system to get accurate results, as very few states are involved. For huge power systems, Prony’s methods can be very useful as it does not involve the computation of the state matrix. From the analysis it is concluded that employing the low inertia machines on the HVDC side would be a safer option as they are vulnerable to faults. The developed study cases are verified in both frequency and time domain and can be used for other studies in future.

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